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Complete List of Authors:	Colyer, Steffi; University of Bath, Department for Health Graham-Smith, Philip; ASPIRE Academy for Sports Excellence, Salo, Aki; Research Institute for Olympic Sports, ; University of Bath, Department for Health
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Abstract:	Ground reaction forces produced on the blocks determine an athlete's center of mass motion during the sprint start, which is crucial to sprint performance. This study aimed to understand how force waveforms are associated with better sprint start performance. Fifty-seven sprinters (from junior to world elite) performed a series of block starts during which the ground reaction forces produced by the legs and arms were separately measured. Statistical parametric mapping (linear regression) revealed specific phases of these waveforms where forces were associated with average horizontal external power. Better performances were achieved by producing higher forces and directing the force vector more horizontally during the initial parts of the block phase (17-34% and 5-37%, respectively). During the mid-push (around the time of rear block exit: ~54% of the block push), magnitudes of front block force differentiated performers, but orientation did not. Consequently, the ability to sustain high forces during the transition from bilateral to unilateral pushing was a performance-differentiating factor. Better athletes also exhibited a higher ratio of forces on the front block in the latter parts of unilateral pushing (81-92% of the block push), which seemed to allow these athletes to exit the blocks with lower center of mass projection angles. Training should reflect these kinetic requirements, but also include technique-based aspects to increase both force production and orientation capacities. Specific training focused on enhancing anteroposterior force production during the transition between double- to single-leg propulsion could be beneficial for overall sprint start performance.

Original Investigation

Corresponding Author:
Dr Aki Salo
KIHU
Rautpohjankatu 6
40700 Jyväskylä
Tel: +358 44 7720 520
Email: aki.salo@kihu.fi

Associations between ground reaction force waveforms and sprint start performance

Steffi L. Colyer[1,2], Philip Graham-Smith[3], and Aki I.T. Salo[1,2,4]

Department for Health, University of Bath, Bath, United Kingdom[1]

CAMERA – Centre for the Analysis of Motion, Entertainment Research and Applications, University of Bath, United Kingdom[2]

Aspire Academy, Doha, Qatar[3]

KIHU Research Institute for Olympic Sports, Jyväskylä, Finland[4]

Abstract

Ground reaction forces produced on the blocks determine an athlete's center of mass motion during the sprint start, which is crucial to sprint performance. This study aimed to understand how force waveforms are associated with better sprint start performance. Fifty-seven sprinters (from junior to world elite) performed a series of block starts during which the ground reaction forces produced by the legs and arms were separately measured. Statistical parametric mapping (linear regression) revealed specific phases of these waveforms where forces were associated with average horizontal external power. Better performances were achieved by producing higher forces and directing the force vector more horizontally during the initial parts of the block phase (17-34% and 5-37%, respectively). During the mid-push (around the time of rear block exit: ~54% of the block push), magnitudes of front block force differentiated performers, but orientation did not. Consequently, the ability to sustain high forces during the transition from bilateral to unilateral pushing was a performance-differentiating factor. Better athletes also exhibited a higher ratio of forces on the front block in the latter parts of unilateral pushing (81-92% of the block push), which seemed to allow these athletes to exit the blocks with lower center of mass projection angles. Training should reflect these kinetic requirements, but also include technique-based aspects to increase both force production and orientation

capacities. Specific training focused on enhancing anteroposterior force production during the transition between double- to single-leg propulsion could be beneficial for overall sprint start performance.

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Introduction

Powerful execution of the block phase is considered crucial for overall success in athletics sprint events. It has consistently been found that the ability to rapidly produce high anteroposterior force is paramount to sprint start performance.[1-3] In fact, across the entire sprint acceleration phase, the highest anteroposterior forces are generated during the block pushing phase.[4]

Previous studies aimed towards elucidating the kinetic factors underlying performance have utilized instrumented blocks[5-7] or starting blocks placed on a single[8,9] or separate force plates[10-13] to measure the forces applied during the sprint start. It is clear that the front leg contributes more to horizontal block exit velocity due to higher impulse generation, which is primarily attributable to a longer push duration compared with the rear leg.[6,11] However, comparisons between sprinters of varying abilities have revealed higher rear block peak forces for elite vs. sub-elite performers with similar (or even lower) front block peak forces reported.[10] Furthermore, Willwacher, Herrmann[5] studied a broad range of sprinters (including both male and female sprinters with a 100-m PB range: 9.58 to 14.00 s) and found rear leg force production to be the most predictive variable of normalized average horizontal external power produced on the blocks, which reflects a sprinter's ability to perform horizontal external work across a short period of time. Importantly, front block force production was also found to significantly contribute to average horizontal external power amongst these athletes, albeit this contribution was less than that of the rear block.[5]

Recently, this analysis has been advanced by Bezodis, Walton[14], who used novel functional data analysis to investigate the ground reaction forces (both the magnitude and direction) produced by sprint start-trained athletes (mean ± SD 100-m PB: 11.37 ± 0.37) during the block phase. Such analysis considers the entire function of the waveforms and identifies characteristics of the curves that differentiate performers, rather than simply comparing discrete features. Bezodis, Walton[14] revealed that rapid rear block force production from the onset of the push and high force production across the entire rear block push duration contributed to higher performance levels. Additionally, although higher front block force production during the first ~25% of the push duration was associated with superior sprint starts, a slower rise to, and a potentially lower, peak force also appeared favorable.[14] This highlights the importance of considering the entire force waveforms and the strength of such approaches over discrete analyses (such as peak force comparisons) where important information can potentially be neglected. In fact, using intra-individual waveform analysis, the initial phase of front leg force production was previously found to be positively associated with average block horizontal external power, whereas the peak was not.[15]

Higher mean ratio of forces or impulses (anteroposterior component vs. resultant), which reflects the ability to direct the force vector horizontally, have also been found to be a further differentiating factors for sprint start performance.[1,5] Such findings align well with those of Otsuka, Shim[16], who documented more horizontally-orientated force vectors in higher-level sprinters. Nonetheless, a certain level of vertical force is clearly required in order to achieve a sufficiently high projection angle to successfully exit the blocks and achieve a flight phase, which allows an athlete to prepare for the first foot contact. Surprisingly, when entire time-series were analyzed using functional data analysis in the recent study by Bezodis, Walton[14], no features relating to force orientation contributed to the prediction of average horizontal external power. The reasons behind this apparent discrepancy with previous discrete analyses[1,5] are not yet clear, but could be related to differences in performance levels between the studies. Accordingly, more research is required to further our understanding of how the orientation of the ground reaction forces applied to the blocks contribute to sprint start performance. The aim of this study was, therefore, to understand how the entire force waveforms produced by a large sample of sprinters (ranging from junior to elite senior) during the block start were associated with the average horizontal external power produced.

Methods

Thirty-seven male senior athletes (mass = 76.0 ± 7.9 kg and height = 1.81 ± 0.07 m; mean ± SD) and 20 male youth academy athletes (mass = 61.6 ± 6.2 kg and height = 1.72 ± 0.07 m) provided informed consent to participate in this study. This included national squad junior, national squad senior and two sub-10 s sprinters. Each participant performed between one and eight maximal-effort block starts. Seventeen of the senior athletes and all of the junior athletes performed 20-40 m accelerations from the blocks on an indoor track. The tests involving the remaining 20 senior athletes were conducted in a laboratory setting in which athletes were asked to maximally accelerate for ~5 m out of the blocks. Although the data were collected in two different locations and running distances varied, the block phase protocol was exactly the same for all athletes. Experimental procedures followed ethical standards in the spirit of the Helsinki Declaration. A University of Bath research ethics committee (REACH) provided ethical approval (EP 16/17 128) for the data to be collected in the laboratory setting. The data on the indoor track were collected as a part of the routine sport science support provided to the athletes, to which all athletes had consented. Nevertheless, to ensure confidentiality, all data were pseudonymised before analysis.

Prior to testing, athletes conducted a self-led or coach-led warm-up including some practice starts. The athletes' preferred block settings were used and spikes were worn throughout the testing. At least four minutes recovery was provided between starts. In both testing locations, four force platforms (two 9287CA and two 9281E on the indoor track and four 9287BA in the laboratory; Kistler Instruments Ltd, Switzerland; sampling at 1000 Hz) covered by synthetic matting were used to collect ground reaction forces under each of the legs and arms separately (Figure 1). These force platform configurations allowed total system load to be measured in the set position, and thus accurately quantify block push duration, impulses and projection angle.[17] Body weight was also collected prior to testing.

[Insert Figure 1]

A 7-point moving average was irreversibly applied to the data captured on the indoor track due to the nature of the testing session and the requirement for information to be quickly fed back. Thus, to ensure data were smoothed identically, a 7-point moving average was also applied to the data collected in the laboratory. Pilot testing revealed that differences in calculated discrete variables (e.g. mean forces and horizontal velocity) due to different force data smoothing methods (7-point moving average or Butterworth low-pass filter with 70 Hz cut-off) were minimal (<0.3%). Anteroposterior and vertical force data from all force plates were summed across each trial from which total resultant force was calculated. Force data were expressed relative to body mass. The ratio of the anteroposterior component to resultant force[3] was also computed. Weight distributions across the rear and front legs, and the arms (combined) in the set position were calculated. Movement onset was defined as the first instant where total vertical force exceeded 20 N above the steady body weight force in the set position and stayed above this threshold for at least 30 ms. Block exit (for the rear and front block) were defined as the first instant when vertical force fell below 20 N.

The impulse-momentum relationship was used to calculate horizontal and vertical velocity from the total forces, and the horizontal impulses generated against each block (rear and front) and by the arms (combined) were also computed separately. Block exit velocity was combined with block push duration to provide average horizontal external power as the performance criterion, which was normalized to body mass.[18] The decreases in total anteroposterior and vertical forces from the initial peak force to the subsequent minimum force (the “dip”, approximately at rear leg block exit) were also calculated (Figure 2). When multiple trials were obtained for an athlete, the trial where average horizontal external power was highest was used in subsequent analyses.

[Insert Figure 2]

Pearson correlations assessed the relationships between the discrete kinetic variables and average horizontal external power. A 0.1 threshold was set for the smallest practically important correlation through which clear (positive or negative) and unclear relationships were defined using 90% confidence intervals (CI).[19] If a correlation coefficient is greater or less than the threshold for the smallest worthwhile correlation ($-0.1 > r > 0.1$) and the 90% confidence intervals do not overlap the opposite smallest worthwhile threshold (±0.1), a relationship is defined as clear. Total force across the block phase and the forces produced on the rear and front block separately (resultant, anteroposterior, vertical and ratio of force) were registered to 101 nodes (0-100% of the block push). Open-source statistical parametric mapping (SPM) software[20] was then used to assess the relationship between the entire force curves and average horizontal external power using previously-described methods.[21]

Results

The mean (± SD) average horizontal external power produced by the group across the block phase was 14.3 ± 2.3 W·kg^{-1}. Figure 3 illustrates the range of average horizontal external power produced by the athletes on the starting blocks.

[Insert Figure 3]

Discrete kinetic variables and their association with average horizontal external power are provided in Table 1. As data from elite sprinters are rare, discrete kinetic variables from five elite, senior athletes (100-m PB times less than 10.15 s) are also presented in Table 1. Higher average horizontal power was exhibited when athletes generated higher relative horizontal impulses on the rear block (r ± 90% CI = 0.60 ± 0.14). Front block relative horizontal impulses were considerably larger than those of the rear block (Table 1; equating to horizontal velocity contributions of 2.26 ± 0.26 m·s^{-1} and 1.09 ± 0.29 m·s^{-1}, respectively) but these were not associated with performance (r ± 90% CI = -0.02 ± 0.22). Overall, total block push duration and horizontal block exit velocity were unsurprisingly the most strongly associated variables with average horizontal external power produced (r ± 90% CI = -0.71 ± 0.11 and 0.81 ± 0.08, respectively). Interestingly, those athletes who exhibited less negative relative horizontal impulse applied by their arms and a higher distribution of weight on their hands produced higher average horizontal external power, although the latter association was weak (r ± 90% CI = 0.44 ± 0.18 and 0.25 ± 0.21, respectively).

[Insert Table 1]

Athletes who exhibited a smaller decrease in anteroposterior force from initial peak to the "dip" also exhibited better sprint start performance (r ± 90% CI = 0.57 ± 0.15). However, no such association was observed for the same force decrement in the vertical direction and more vertical center of mass projection angles were negatively associated with block performance, yet this relationship was weak (r ± 90% CI = -0.26 ± 0.20).

Analysis of the entire force waveforms revealed positive associations between resultant force and average horizontal external power from 17-34% and 54-74% of the block push (Figure 4). Additionally, higher ratio of forces (more horizontal force orientation) were associated with higher average horizontal external power during the initial (5-37%) and latter (83-90%) parts of the block phase (Figure 4). In the anteroposterior direction, positive associations were observed from 17-34% and 55-72% ($p < 0.001$) of the total push duration. Similarly, in the vertical direction, forces were positively associated with average horizontal external power from 19-33% and 54-74% ($p < 0.001$).

[Insert Figure 4]

When the same waveform analysis was conducted on the separate blocks, resultant force produced on the rear block was positively associated with performance from 13-67% (Figure 5) of the rear block push duration. Positive performance associations were also observed for ratio of forces and the anteroposterior force component produced on the rear block from 3-54% and 6-68% of the rear block push, respectively (Figure 5). The vertical force component was also positively associated with performance from 19-64% rear block push duration. For the front block, ratio of forces was positively associated with average horizontal external power from 0-30% and 81-92% (Figure 6). For the resultant force and both the anteroposterior and vertical components of force, the waveforms were positively associated with performance for a short period (51-67%, 50-66%, 54-66% of front block push, respectively), around the time of rear block exit (~54%). An association with performance was also observed for the anteroposterior force component in the early push phase (between 6-19%; Figure 6).

[Insert Figure 5]
[Insert Figure 6]

Discussion

This study has identified the specific phases of force production that are associated with higher average horizontal external power generated during the block phase in a large group of sprinters, which includes two sub-10-s 100-m sprinters. Comparisons with previous studies reveal that some of the participants in the current study were within the range of athletes previously classified as “elite” or “world class”. For example, one athlete in the current study exited the blocks with 3.77 $m \cdot s^{-1}$ of horizontal velocity with only a 0.379-s push duration, whereas the “elite” group in the Rabita, Dorel[1] study (medalists at major championships or Olympic finalists) exhibited an average block exit velocity of 3.61 $m \cdot s^{-1}$ and a block push duration of 0.376 s.

In line with previous studies,[1,5] the ability to generate large amounts of force to reach higher block exit velocities across short block push durations differentiated block phase performance. Both higher magnitudes of force and more horizontally-orientated force vectors were associated with higher performance levels, particularly in the initial ~30% of the block phase (i.e. before the hands leave the ground). Additionally, better athletes produced less negative horizontal impulse under their hands, which could be linked to more weight being distributed on the hands compared with their slower counterparts (Table 1). Despite being lower than that of the front block, rear block relative horizontal impulse (equating to a horizontal velocity contribution of 1.09 ± 0.29 $m \cdot s^{-1}$ compared to 2.26 ± 0.26 $m \cdot s^{-1}$ for the front block) was found to be more strongly associated to performance. Additionally, waveform analyses revealed substantially more marked supra-threshold clusters (Figure 5) compared with the front (Figure 6). This reinforces the importance of rear block force production to average horizontal external power on the blocks.[5,10] However, higher front block force production during the transition (when the rear foot leaves the block, ~54% of the block push) and a more horizontally orientated front-block force vector late in the block phase (81-92%) were also uncovered as important performance-differentiating factors.

Higher average ratio of forces produced on the blocks and lower projection angles were both associated with average horizontal external power (r ± 90% CI = 0.68 ± 0.12 and -

0.26 ± 0.20, respectively), supporting the notion that sprinters should orientate the force vector more horizontally to improve block performance.[1,5,16] This seemed to be particularly important in the initial phases of the block phase (5-37% of the block push, when the hands were still in contact with the ground). However, clearly some level of vertical force production is needed in order to exit the block successfully and thus, optimization rather than minimization of this angle is likely to be key for successful performance. In fact, the SPM results illustrated in Figure 4 suggested that after the hands left the ground, better sprint start performers do not orientate the force vector more horizontally than their weaker counterparts during the mid-block phase (until 83% of the block push). This could reflect a necessary strategy whereby athletes delay an increase in front foot anteroposterior force production to ensure the center of mass is positioned favorably and to avoid over-rotation before forceful extension of the front leg in the late block phase. This may allow a more horizontal projection angle and a more effective block exit to be achieved.

Athletes who produced a greater mean vertical force component in the current study also exhibited higher average horizontal external power on the blocks (Table 1). Specifically, vertical force production in the initial parts of the block phase and shortly after rear block exit (19-33% and 54-74% of the block push, respectively) were positively related to performance. Vertical force production does not directly contribute to sprint performance *per se*. However, applying vertical force is needed to raise the athlete's center of mass from the crouched starting position and to attain sufficient vertical velocity, which allows an athlete enough time during the flight phase to prepare for the first ground contact.

Interestingly, when the athletes transitioned from bilateral to unilateral pushing (rear block exit; ~54% of the block push) positive performance associations were observed for resultant force and both the anteroposterior and vertical components (54-74%, 55-72% and 54-74% of the block push, respectively; Figure 4). This was also observed in the front block force analysis where positive performance associations were observed during this middle section of the push (e.g. 51-67% of the block push for resultant force, Figure 6). Thus, balance, stability and potentially confidence through this phase may allow individuals to sustain higher forces, transition more effectively between bilateral and unilateral pushing and ultimately perform an overall superior sprint start. To our knowledge this is the first study to reveal such associations in the transition phase of the sprint start, and thus more research is warranted to better understand how training can be prescribed to improve this seemingly important skill.

Willwacher, Herrmann[5] previously found the magnitude of force application on the rear block to be the most predictive discrete factor of sprint start performance. In line with previous waveform analyses,[14] the generation of this rear block force from early in the block pushing phase appears important for average horizontal power generation (Figure 5). Additionally, a smaller decrease in anteroposterior force from the first peak to the "dip" (which coincides with the period from the hands leaving the ground to rear block exit) was also positively associated with overall block average horizontal external power (r = 0.57 ± 0.15). Thus, successful athletes are those who are able to generate high peak rear block force during the early block phase (when the upper limbs are able to provide an anchor to push against), but also to maintain this high force production during the bilateral pushing phase until the rear foot exits the blocks. Considering the waveform and discrete analyses collectively, athletes who exhibited a lower initial peak in anteroposterior force, but were able to maintain this force across the rear block push duration, performed the sprint start to a similar level to those who exhibited a very high initial peak, but were unable to maintain this high force. Factor analysis conducted in a previous study has alluded to the existence of individual force production strategies for the front block.[5]

Higher ratio of forces was observed in higher-level performers from the onset of force production (0-30% of the front block push and 3-54% for the rear) and towards the latter phases of the push duration (81-92%). Collectively, these findings suggest that better athletes achieve a more horizontally-orientated force vector during the initial push and latter parts of the push. Interestingly, Bezodis, Walton[14] did not find any associations between the force vector orientation at either block. It is unclear why such discrepancies exist. Although the waveform analysis techniques differ across these studies, it was recently shown that similar inferences are drawn when they are applied to the same data.[22] Consequently, it is perhaps more likely that between-study differences in ability levels and perhaps the sports in which the participants specialized in could contribute to this inconsistency. For example, the sprinters in the current study produced mean average horizontal external power of 14.3 ± 2.3 W·kg^{-1}, whereas the previous study by Bezodis, Walton[14] included a mix of sprinters, jumpers and decathletes who produced average horizontal external power of 12.5 ± 1.7 W·kg^{-1}. More research is certainly required to better understand these differences and assess the potential for the association between force orientation and performance to be mediated by ability level.

It should be noted that as the block push duration varied across athletes (SD = 0.039 s), some temporal information could potentially have been masked by normalizing the force curves to 101 nodes. Nonetheless, the SPM analysis conducted here still reflects important differences in force at the same relative part of the block phase. Furthermore, alternative discrete analyses can capture further temporal information, which may be of interest to practitioners and coaches (e.g. rate of force development). We advocate this combined approach when attempting to fully evaluate sprint acceleration performance. The importance of this was highlighted by the aforementioned apparent discrepancy between the performance associations with the discrete (decrease from the peak anteroposterior force to the dip) and the waveform analysis across this transition. Whilst this sample spanned a broad range of abilities, it included both senior and junior athletes. Although the abilities of these groups overlapped (Figure 3), some of the performance-differentiating factors (e.g. the transition) could conceivably reflect differences between youth and senior athletes. More research is required to better understand the timeline of junior athletes' progress and how training can promote this development. Such information would greatly contribute to talent-development pathways and guide training practices of young athletes.

Conclusion

Producing high forces with a more horizontal orientation should be encouraged from the onset of the push against both the rear and front block. However, during the middle part of the push (around rear block exit), the magnitude of front block force production was a more performance-differentiating factor than the orientation. This could conceivably be attributed to between-athlete differences in balance and stability when transitioning from the bilateral to unilateral pushing action. In the latter phases of the front block push duration (81-92%) producing a high ratio of forces was again associated with higher performance levels, which was perhaps a strategy to reduce the center of mass projection angle at block exit. Training should reflect these demands and aim to increase both physical (force production) but also technical (force orientation) capacities to enhance an athlete's sprint start performance. Specifically, practitioners should perhaps strive to enhance an athlete's force production during the transition phase by prescribing specific unilateral training exercises (e.g. single-leg hip thrust).

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Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Figure Captions

Figure 1. A schematic of the experimental set-up in the laboratory (left) and the indoor track (right) sessions. Rectangles depict force plates and grey bars represent the spines of the blocks with black squares and circles representative of block and hand positions, respectively.

Figure 2. A schematic illustrating the calculation of the decrease in force from the peak to the dip (δ). Horizontal dashed black lines indicate force value at the peak and the dip. Vertical dashed red line represents the time point when the rear leg exited the block.

Figure 3. Average horizontal external power produced by junior (circles) and senior (crosses) athletes during the block phase.

Figure 4. Mean ground reaction force curves (upper row from left to right: resultant, ratio of forces, anteroposterior and vertical; grey shading represents standard deviations) and the corresponding SPM results (*t* curves; lower row) depicting the relationships between force and average horizontal external power across the block phase. Grey shaded areas indicate significant ($\alpha = 0.05$) relationships between at those time nodes. Vertical black and red dashed lines indicate the average nodes when the hands left the ground (38% of the block push) and rear foot exited the block (54% of the block push), respectively.

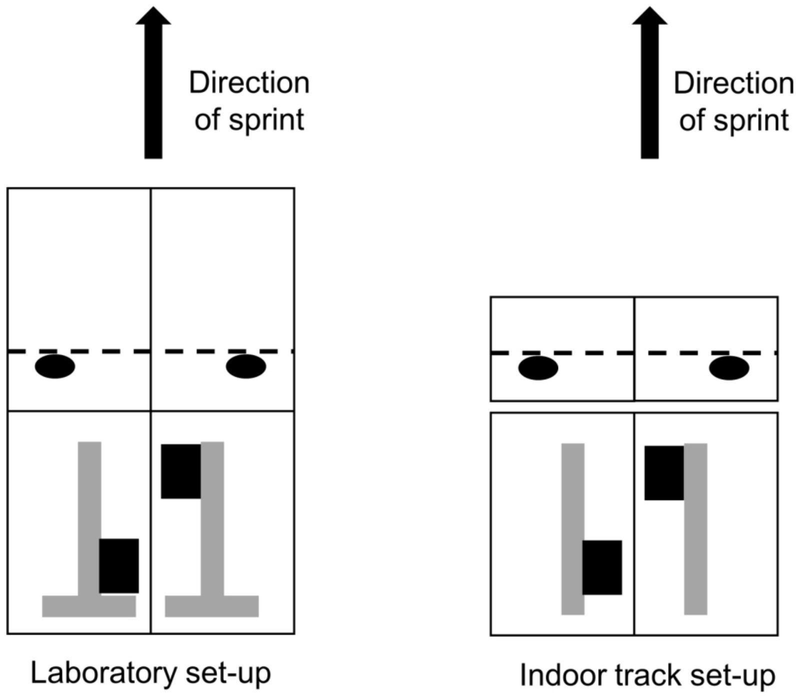
Figure 5. Mean ground reaction forces produced against the rear block (upper row from left to right: resultant, ratio of forces, anteroposterior and vertical; shading represents standard deviations) and the corresponding SPM results (*t* curves; lower row) depicting the relationships between force curves and average horizontal external power across the rear block push phase. Grey shaded areas indicate significant ($\alpha = 0.05$) relationships at those time nodes.

Figure 6. Mean ground reaction forces produced against the front block (upper row from left to right: resultant, ratio of forces, anteroposterior and vertical; shading represents standard deviations) and the corresponding SPM results (*t* curves; lower row) depicting the relationships between force curves and average horizontal external power across the front block push phase. Grey shaded areas indicate significant ($\alpha = 0.05$) relationships at those time nodes. Vertical red dashed lines indicate the average nodes when the rear foot exited the block (54% of the block push).

Table 1. Discrete kinetic variables and the association with average horizontal power produced across the block phase.

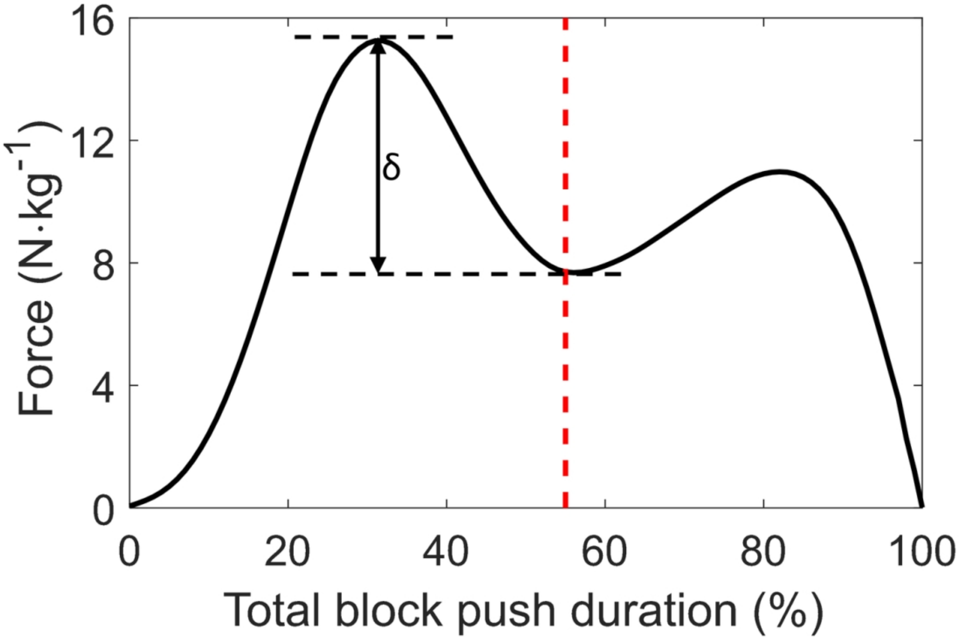
	Mean ± SD	***r* ± 90% CI**	**Elite sprinters Mean ± SD**
Total block push duration (s)	0.390 ± 0.039	**-0.71 ± 0.11**	0.360 ± 0.010
Block exit horizontal velocity ($m \cdot s^{-1}$)	3.30 ± 0.20	**0.81 ± 0.08**	3.36 ± 0.13
Block exit vertical velocity ($m \cdot s^{-1}$)	0.60 ± 0.11	0.00 ± 0.22	0.58 ± 0.06
Mean anteroposterior force ($N \cdot kg^{-1}$)	8.7 ± 1.1	**0.87 ± 0.06**	9.4 ± 0.1
Mean vertical force ($N \cdot kg^{-1}$)	14.7 ± 0.7	**0.83 ± 0.07**	15.1 ± 0.2
Mean ratio of force (%)	57.5 ± 6.2	**0.68 ± 0.12**	56.1 ± 4.8
Front block relative horizontal impulse (BW·s)	0.230 ± 0.026	-0.02 ± 0.22	0.247 ± 0.015
Rear block relative horizontal impulse (BW·s)	0.112 ± 0.030	**0.60 ± 0.14**	0.106 ± 0.017
Arms relative horizontal impulse (BW·s)	-0.005 ± 0.004	**0.44 ± 0.18**	-0.004 ± 0.003
Centre of mass projection angle (°)	10.3 ± 2.0	**-0.26 ± 0.20**	9.8 ± 0.8
Proportion of weight on the hands in the set position (%)	70.4 ± 7.4	**0.25 ± 0.21**	72.7 ± 2.0
Proportion of weight on the rear block in the set position (%)	15.7 ± 5.1	**-0.19 ± 0.21**	17.3 ± 5.3
Proportion of weight on the front block in the set position (%)	13.9 ± 7.0	-0.13 ± 0.23	10.0 ± 5.7
Change in anteroposterior force from peak to dip (N/kg)	-10.6 ± 2.5	**0.57 ± 0.15**	-10.3 ± 3.1
Change in vertical force from peak to dip ($N \cdot kg^{-1}$)	-9.9 ± 2.2	0.05 ± 0.22	-10.6 ± 2.1

CI = confidence intervals. Bold denotes clear associations. “Elite sprinters” group includes five sprinters with 100-m PB times less than 10.15 s (two sub 10-s sprinters).



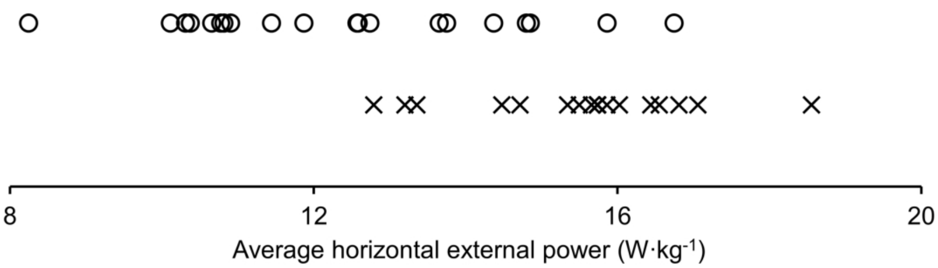
A schematic of the experimental set-up in the laboratory (left) and the indoor track (right) sessions. Rectangles depict force plates and grey bars represent the spines of the blocks with black squares and circles representative of block and hand positions, respectively.

159x129mm (300 x 300 DPI)



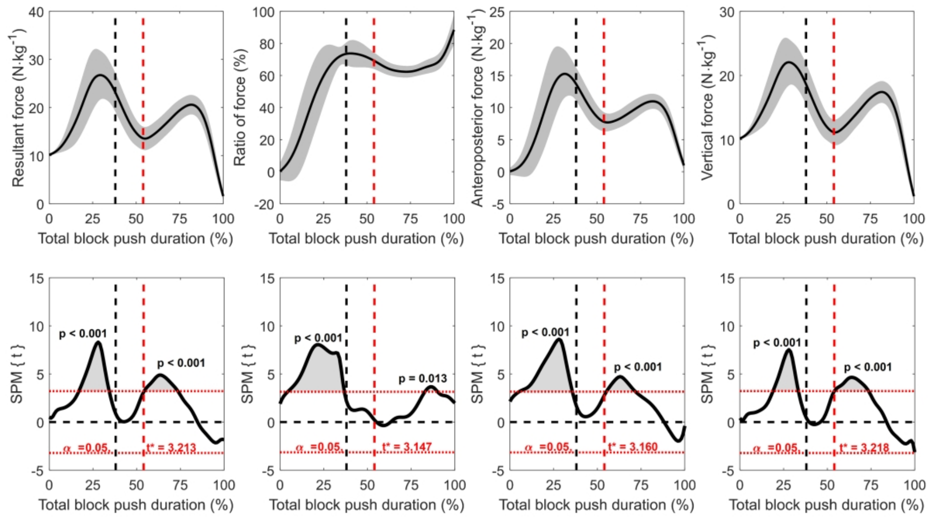
A schematic illustrating the calculation of the decrease in force from the peak to the dip (δ). Horizontal dashed black lines indicate force value at the peak and the dip. Vertical dashed red line represents the time point when the rear leg exited the block.

124x85mm (300 x 300 DPI)



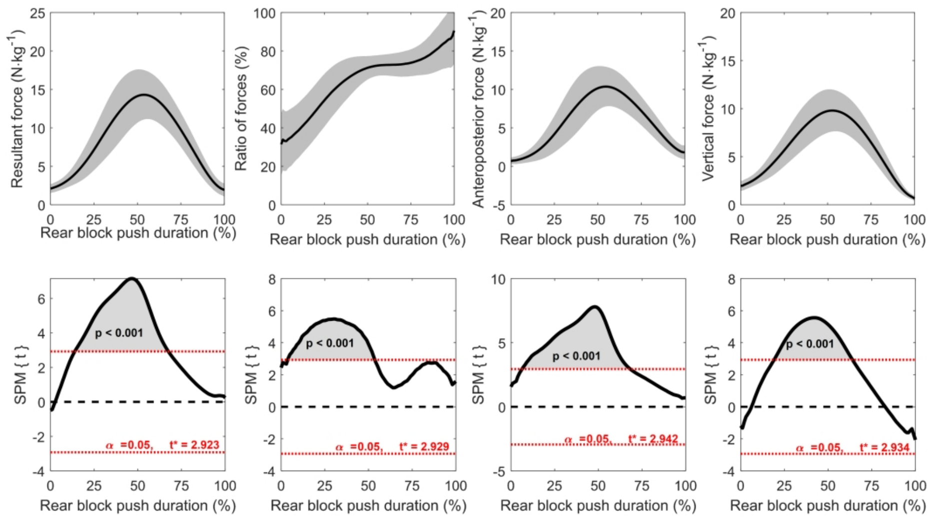
Average horizontal external power produced by junior (circles) and senior (crosses) athletes during the block phase.

169x49mm (300 x 300 DPI)



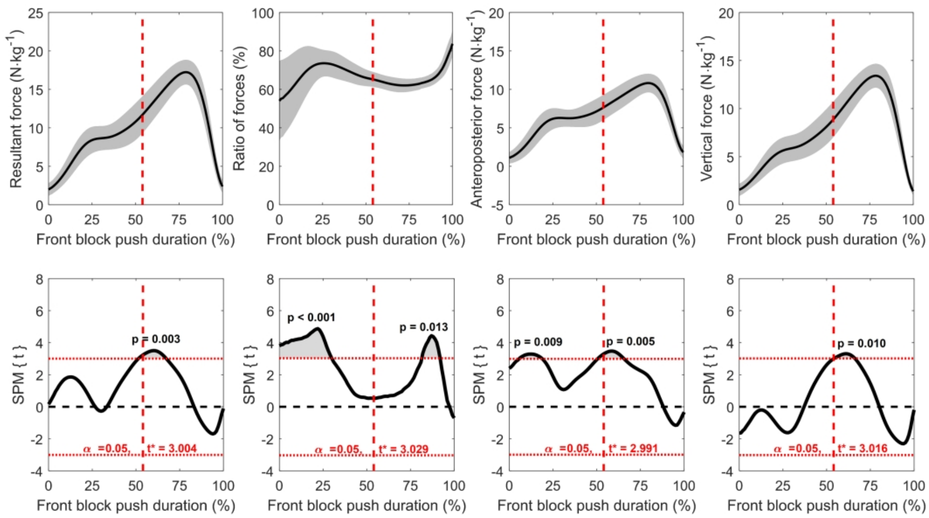
Mean ground reaction force curves (upper row from left to right: resultant, ratio of forces, anteroposterior and vertical; grey shading represents standard deviations) and the corresponding SPM results (*t* curves; lower row) depicting the relationships between force and average horizontal external power across the block phase. Grey shaded areas indicate significant (α = 0.05) relationships between at those time nodes. Vertical black and red dashed lines indicate the average nodes when the hands left the ground (38% of the block push) and rear foot exited the block (54% of the block push), respectively.

288x150mm (300 x 300 DPI)



Mean ground reaction forces produced against the rear block (upper row from left to right: resultant, ratio of forces, anteroposterior and vertical; shading represents standard deviations) and the corresponding SPM results (*t* curves; lower row) depicting the relationships between force curves and average horizontal external power across the rear block push phase. Grey shaded areas indicate significant (*α* = 0.05) relationships at those time nodes.

288x150mm (300 x 300 DPI)



Mean ground reaction forces produced against the front block (upper row from left to right: resultant, ratio of forces, anteroposterior and vertical; shading represents standard deviations) and the corresponding SPM results (*t* curves; lower row) depicting the relationships between force curves and average horizontal external power across the front block push phase. Grey shaded areas indicate significant (*α* = 0.05) relationships at those time nodes. Vertical red dashed lines indicate the average nodes when the rear foot exited the block (54% of the block push).

288x150mm (300 x 300 DPI)